

# H<sub>2</sub> in Galaxies

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The bulk of the molecular gas in spiral galaxies is under the form of cold H<sub>2</sub>, that does not radiate and is only suspected through tracer molecules, such as CO. All tracers are biased, and in particular H<sub>2</sub> could be highly underestimated in low metallicity regions. Our knowledge is reviewed of the H<sub>2</sub> content of galaxies, according to their types, environment, or star-forming activities. The HI and CO components are generally well-mixed (spiral arms, vertical distribution), although their radial distributions are radically different, certainly due to radial abundance gradients. The hypothesis of H<sub>2</sub> as dark matter is discussed, as well as the implications on galaxy dynamics, or the best perspectives for observational tests.

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## 1. How to observe H<sub>2</sub> in galaxies?

The bulk of molecular hydrogen in a galaxy is cold, around 10-20K, and therefore invisible. The first rotational level, accessible only through a quadrupolar transition, is more than 500 K above the fundamental. The presence of H<sub>2</sub> is inferred essentially from the CO tracer. The carbon monoxide is the most abundant molecule after H<sub>2</sub>; its dipole moment is small (0.1 Debye) and therefore CO is easily excited, the emission of CO(1-0) at 2.6mm (first level at 5.52K) is ubiquitous in the Galaxy.

### 1.1. The H<sub>2</sub>/CO conversion ratio

To calibrate the H<sub>2</sub>/CO ratio, the most direct and natural is to compare the UV absorption lines of CO and H<sub>2</sub> along the same line of sight (Copernicus, e.g. Spitzer & Jenkins 1975; ORFEUS, cf Richter et al., this conference). However, only very low column densities are accessible, in order to see the background source, and therefore these observations sample only the diffuse gas, which is not representative of the global molecular component. It is well known now that the conversion ratio might vary considerably from diffuse to dense gas (see below). The CO molecule is excited by H<sub>2</sub> collisions, and should be a good tracer; but its main rotational lines are most of the times optically thick. One can then think of observing its isotopic substitutes <sup>13</sup>CO or C<sup>18</sup>O, but these are poor tracers since they are selectively photodissociated, and trace only the dense cores.

The main justification to use an H<sub>2</sub>/CO conversion ratio is the Virial hypothesis: in fact, the CO profiles do not yield the column densities, but they give the velocity width  $\Delta V$  of molecular clouds. Once the latter are mapped, and their size  $R$  known, the virial mass can be derived, proportional to  $\Delta V^2 R$ . There exists a good relation between the CO luminosity and the virial mass, as shown in Figure 1. The relation has a power-law shape, but with a slope different from 1. Both are not proportional, and the conversion ratio should vary by more than a factor 10 from small to Giant Molecular Clouds (GMC). In external galaxies, the observations provide only an average over many clouds, and it has been hoped that the clouds are of the same nature from galaxy to galaxy. If  $T_b$  is the brightness temperature of the average cloud, the conversion ratio  $X$  should vary as  $n^{1/2}/T_b$ , where  $n$  is the average density of the cloud. This does not take into account the influence of the gas metallicity. And the CO luminosity varies with the metallicity  $Z$ , sometimes more than linearly. In the Magellanic Clouds, LMC or SMC (Rubio et al 1993), the conversion ratio  $X$  might be 10 times higher than the "standard" ratio. The

ratio can be known for local group galaxies, since individual clouds can be resolved, and virial masses computed (Wilson 1995).

### 1.2. *Dust as a tracer*

At millimetric wavelengths, in the Rayleigh-Jeans domain, dust emission depends linearly on temperature, and its great advantage is its optical thinness. In some galaxies, CO and dust emission fall similarly with radius, like in NGC 891 (Guélin et al. 1993). In other, such as NGC 4565 (Neininger et al. 1996), the dust emission falls more slowly than CO, although more rapidly than HI emission. This can be interpreted by the exponential decrease of metallicity with radius. The dust/HI ratio follows this dependency, while CO/HI is decreasing more rapidly (either due to metallicity, or excitation problems).

### 1.3. *Gamma-rays*

Their emission is proportional to the product of the Cosmic Ray density and the gas density. But both densities, and their radial profiles are not known independently. The  $\gamma$ -ray radial distribution is however much more extended than that of the supernovae remnants, the source of cosmic ray acceleration (e.g. Bloemen 1989). Recently: EGRET onboard GRO has observed an excess of gamma-rays in the halo of our Galaxy (see below).

### 1.4. *Direct H<sub>2</sub> observations*

Of course, H<sub>2</sub> can also be observed directly when it is warm. Starbursts and mergers reveal strong 2.2  $\mu$ m emission, like in NGC 6240 (DePoy et al 1986). The source of excitation has long been debated (X-ray heating, UV fluorescence, shocks...) and it was recently concluded that global shocks were responsible (van der Werf et al. 1993, Sugai et al. 1997). Pure rotational lines have been observed with ISO. In Arp220, as much as 10% of the ISM could be in the warm phase, i.e.  $3 \cdot 10^9 M_{\odot}$  (Sturm et al. 1996) while CO observations conclude to a total  $M(H_2) = 3.5 \cdot 10^{10} M_{\odot}$  (Scoville et al. 1991). In normal galaxies, the warm H<sub>2</sub> could be less abundant (Valentijn et al. 1996). At least, the warm CO component does not affect the H<sub>2</sub>/CO ratio.

## 2. CO and H<sub>2</sub> content of galaxies

From a CO survey of more than 300 galaxies, it has been concluded that the average molecular content was comparable to the atomic content:  $M(H_2)/M(HI) \sim 1$  (Young & Knezek 1989; Young & Scoville, 1991). But most of galaxies in this survey were selected from their IRAS flux, and this could introduce a bias. A recent survey by Casoli et al (1998) near the Coma cluster has shown an average  $M(H_2)/M(HI) \sim 0.2$ .

### 2.1. *Variation with morphological type*

It is well established that the HI component is proportionally more abundant relative to the total mass in late-type galaxies. The opposite trend is observed for the H<sub>2</sub>, at least as traced by the CO emission.  $M(H_2)/M(HI)$  is therefore smaller for late-types, by a factor  $\sim 10$ . However, this could be entirely a metallicity effect. Since the metallicity is increasing with the mass of the galaxy, a test is to select the most massive galaxies of late-type. For these high-mass galaxies, there is no trend of decreasing H<sub>2</sub> fraction with type (Casoli et al. 1998).

### 2.2. *Dwarf and LSB galaxies*

The strong dependency of the H<sub>2</sub>/CO conversion ratio on metallicity Z is also the main problem in the observations of dwarf and Low Surface Brightness (LSB) galaxies. Both

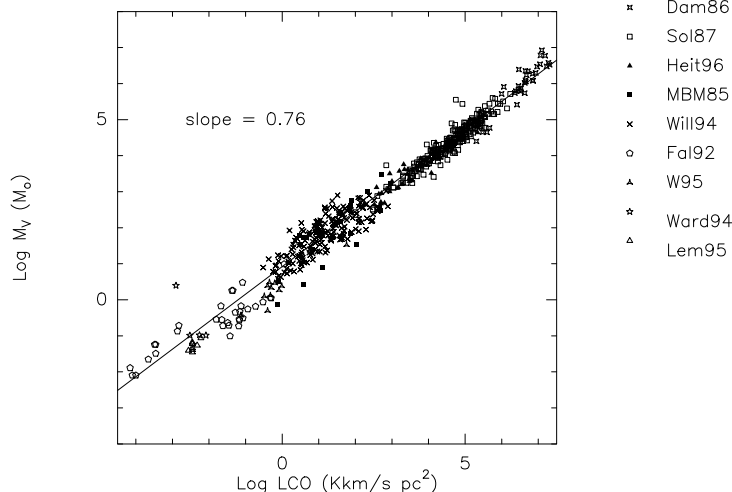


FIGURE 1. Virial mass versus CO luminosity for molecular clouds in the Milky Way. The fit corresponds to  $M_V \propto L_{CO}^{0.76}$ . The data are from Dam86: Dame et al. (1986); Sol87: Solomon et al. (1987); Heit96: Heithausen (1996); MBM85: Magnani et al. (1985); Will94: Williams et al. (1994); Fal92: Falgarone et al. (1992); W95: Wang et al. (1995); Ward94: Ward-Thompson et al. (1994); Lem95: Lemme et al. (1995).

have low metallicity. It appears that the conversion factor  $X$  can vary linearly and even more with metallicity, as predicted by Maloney & Black (1988). Not only, the low abundance of C and O lowers the abundance of CO, but also the dust is less abundant, and therefore the UV light is less absorbed, and spread all over the galaxy, photo-dissociating the CO molecules. When the dust is depleted by a factor 20, there should be only 10% less  $H_2$ , but 95% less CO (Maloney & Black 1988).

In dwarf galaxies, CO emission is very low, and it is difficult to know the  $H_2$  content. If the  $HI/H_2$  ratio is assumed constant from galaxy to galaxy, then  $X$  varies with  $Z^{-2.2}$  (Arnault et al 1988). Recent results by Barone et al (1998), Gondhalekar et al (1998) and Taylor et al (1998) confirm this strong dependency on metallicity, increasing sharply below 1/10th of solar metallicity.

Low-surface-brightness galaxies have large characteristic radii, large gas fraction and are in general dark matter dominated; they are quite unevolved objects. Their total gas content is similar to that of normal galaxies (McGaugh & de Blok 1997). But CO is not detected in LSB (de Blok & van der Hulst 1998). Due to their low surface density, below the threshold for star formation, these galaxies have a very low efficiency of star formation (Van Zee et al 1997). The cause could be the absence of companions, since LSB live in poor environments (Zaritsky & Lorrimer 1993). It is well known that galaxy interactions, by driving in a high amount of gas, trigger star formation.

### 2.3. Ultra-luminous IRAS galaxies

At the opposite, there exists a class of galaxies, characterized by their bursts of star formation; these are ultra-luminous in far-infrared, because of the emission of dust heated by the new stars. These objects possess large amounts of gas, particularly condensed in the inner parts, certainly due to interactions and mergers. CO emission is highly enhanced in these starbursting galaxies, and large  $H_2$  masses are deduced, even with a modified (lower than standard) conversion ratio (Solomon et al 1997). The prototype of these objects is the nearby Arp220: new CO interferometer data show that CO is

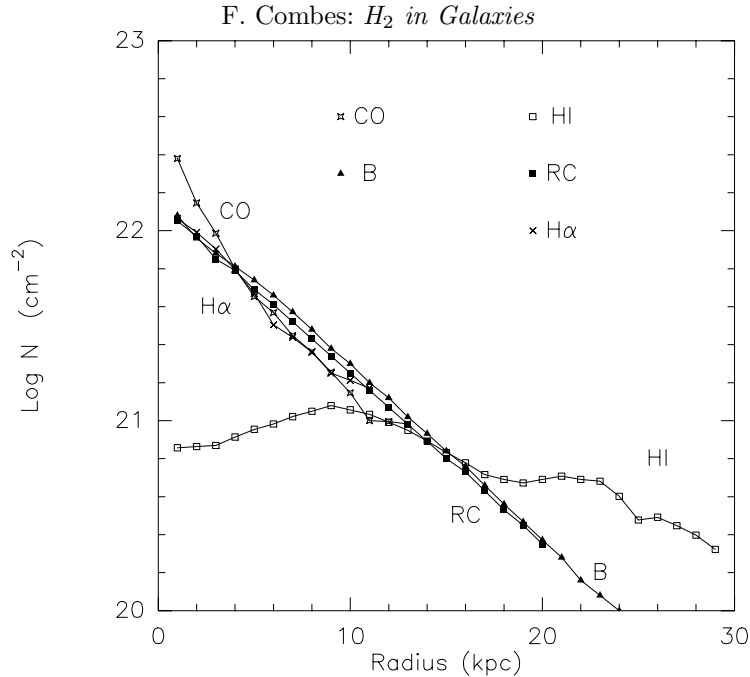


FIGURE 2. Radial distributions of various surface densities in a typical spiral galaxy NGC 6946:  $H_2$ (CO) and HI column densities, Blue, Radio-continuum and  $H\alpha$  surface densities (adapted from Tacconi & Young, 1986).

in rotating nuclear disks (Downes & Solomon 1998), where the surface density of gas is about 30% of the total surface density.

### 3. Spatial distribution

#### 3.1. Radial Distributions

The differences between HI and  $H_2$  (or CO) radial distributions in galaxies is striking (cf figure 2). While all components related to star formation, the blue luminosity from stars, the  $H\alpha$  (gas ionised by young stars), the radio-continuum (synchrotron related to supernovae), and even the CO distribution, follow an exponential distribution, the HI gas alone is extending much beyond the “optical” disk, sometimes in average by a factor 2 to 4 ( $R_{HI} = 2-4 R_{opt}$ ). The HI gas has very often a small deficiency in the center. Would this mean that the atomic gas is transformed in molecular phase in the denser central parts? This is possible in some galaxies, where the HI and CO distribution appear complementary, but it is not the general case, all possibilities have been observed, including a central gaseous hole, both in CO and HI (like in M31, for example).

#### 3.2. Large-scale Structure

Within the optical disk, where CO is observed easily, there is a very good large-scale correlation between both gas components (see e.g. Neininger et al. 1998). They appear well mixed, and follow the spiral arms with large contrast. This is also true for the ionised gas (HII regions). Of course, this is only at 100pc-1kpc scale; at very small scale the various components can be anti-correlated, the HI gas being found more at the envelopes of dense molecular clouds, the ionised gas being also anti-correlated with the neutral gas.

### 3.3. Vertical Structure

In our own Galaxy, and in external galaxies seen edge-on, the galaxy disks appear much narrower in CO emission than in HI. This suggests that the molecular gas is more confined to the plane, and that its vertical dynamical oscillations are of less amplitude than for the atomic gas. The consequence should be a vertical velocity dispersion much lower for the molecular gas, since for a given restoring force due to the stellar disk, the maximum height above the plane is proportional to the z-velocity dispersion. Surprisingly, this is not the case: in face-on galaxies both CO (Combes & Becquaert 1997) and HI (Kamphuis 1992) velocity dispersions are observed of similar values ( $\sigma_v \sim 6$  km/s), and remarkably constant with radius. This is not a saturation effect of the CO lines, since the <sup>13</sup>CO spectra show the same. A possible interpretation is that both gas are well mixed, in fact it is the same dynamical component, which changes phase along its vertical oscillations. It is possible that the H<sub>2</sub> gas follows the HI, but the CO is photo-dissociated at high altitudes, or not excited. Or even the H<sub>2</sub> could disappear, since the chemistry time-scale ( $\sim 10^5$  yr) is much smaller than the dynamical z-time-scale ( $\sim 10^8$  yr).

### 3.4. Small scale structure of clouds

The molecular component is also characterized by its remarkable self-similar structure, a hierarchical system of clouds, tightly related to a fractal structure. It can be quantified by power-law relations between cloud size and linewidth, or size and mass (Larson, 1981). These relations are observed, whatever the radial distance to the center, and in the HI component as well. The fact that the same structure is observed outside of the star-forming regions is puzzling: the HI gas outside the optical disk displays a very clumpy structure, implying that it is unstable at all scales (spiral arms, self-similar structure of clumps). The fact that these gravitational instabilities do not trigger star formation must be explained.

## 4. H<sub>2</sub> as a dark matter candidate

One of the driver to propose cold H<sub>2</sub> as a dark matter candidate is our increasing knowledge about evolution of galaxies along the Hubble sequence (e.g. Pfenniger, Combes & Martinet, 1994). Because of spiral waves and bars, galaxies progressively concentrate their mass towards the center, and the late-type galaxies evolve to early-types in the sequence. Besides, HI observations of rotation curves have shown that the fraction of dark matter in the total mass is larger in late-type galaxies: therefore, some of the dark matter must be transformed into stars during evolution (cf Pfenniger, this conference).

### 4.1. Baryonic mass fraction

The quantity of baryons in the Universe (and more precisely the fraction of the critical density in baryons  $\Omega_b$ ) is constrained by the primordial nucleosynthesis to be  $\Omega_b = 0.013 h^{-2}$ , with  $h = H_0/(100 \text{ km/s/Mpc})$  is the reduced Hubble constant. With  $h = 0.5$ ,  $\Omega_b$  is 0.09, and more generally  $\Omega_b$  is between 0.01 and 0.09 (Walker et al. 1991, Smith et al. 1993), while the visible matter corresponds to  $\Omega_* \sim 0.003 (M/L/5) h^{-1} (+ 0.006 h^{-1.5})$  for hot gas). Therefore, most of the baryons (90%) are dark.

In rich clusters of galaxies, the baryons are more visible, under the form of hot gas, they constitute  $\sim 30\%$  of the total mass (White et al. 1993). Since clusters must be representative of the baryonic fraction of the Universe, this implies that the total mass cannot be larger than 3 times the baryons mass (or  $\Omega_m < 0.3$ ).

#### 4.2. *The smallest fragments*

The existence of a large number of gas clumpuscles (of  $\sim 10$  AU in size) in the Galaxy has already been invoked to explain the observed ESE (Extreme Scattering Events) in front of quasars, by Fiedler et al. (1987, 1994). About 300 QSOs were observed during a few years, 150 over 12 yrs. More than 10 ESE events were detected, due to diffraction or refraction by a region of high electronic density ( $n_e$ ). From the duration of the events, sizes of  $\sim 10$  AU are derived, and from their frequency, the number of clumpuscles in the Galaxy must be about  $10^3$  the number of stars. The neutral density of these objects is still a matter of debate. Their stability is best explained in the hypothesis that they are self-gravitating. The mass of one clumpuscle is then of the order of  $10^{-3} M_\odot$ . Walker & Wardle (1998) have recently built models of self-gravitating clouds, with envelopes ionised by the interstellar radiation field: they found for the electronic density the right order of magnitude to account for the observed ESE. This hypothesis is supported by direct observations through HI VLBI in absorption in front of remote radio sources (Diamond et al. 1989, Davis et al. 1998, Faison et al. 1998); large column densities ( $\sim 10^{21} \text{ cm}^{-2}$ ) are observed with sizes of  $\sim 10$  AU, leading to HI densities of  $10^6 \text{ cm}^{-3}$  or more.

#### 4.3. *Gamma-rays*

Dixon et al. (1998) from EGRET observations have recently detected an excess of diffuse  $\gamma$ -ray emission in the galactic halo. This could be interpreted in several ways: either coming from un-resolved sources associated to the Galaxy; or being due to high-latitude inverse compton emission; or finally to extra molecular gas in the halo, through cosmic ray/nucleon reaction giving  $\pi_0$  then  $\gamma$ -rays. This has been developped by de Paolis et al. (1999) and Kalberla et al. (1999), see also Shchekinov (this conference). Cosmic rays are stopped by thick clumpuscles, that have enough column density to be opaque for both cosmic rays and gamma rays. Sciama (1999) proposes that cosmic rays are fragmented in clouds, heat the clouds, and are responsible for the their FIR emission (Sciama 1999). However, the absorbed energy is non negligible, and since clouds in these halo models are assumed to move through the optical plane (in their z-ocillations), sweep up high-metallicity gas, and therefore contain CO molecules, they should be visible through CO emission.

#### 4.4. *Various models of H<sub>2</sub> as dark matter*

The first model proposes to prolonge the visible gaseous disk towards large radii, with thickening and flaring, following the HI disk. The cold and dark H<sub>2</sub> component is supported by rotation, exists only outside the optical disk, where it is required by rotation curves (Pfenniger et al 1994, Pfenniger & Combes 1994). The gas is stabilised through a constantly evolving fractal structure, experiencing Jeans instabilities at all scales, in thermal equilibrium with the cosmic background radiation at  $T = 2.7 (1+z)$  K.

Other models distribute the dark molecular gas in a spherical or flattened halo, with no hole within the optical disk. The molecular gas is not so cold, and is associated with clusters of brown dwarfs or MACHOS (de Paolis et al. 1995, Gerhard & Silk 1996, Shchekinov, this conference).

In the clumpuscle model, the HI gas can be considered as a tracer, the interface between the molecular clumps and the extra-galactic radiation field. Beyond the HI disk, there could be an ionization front, and the interface might become ionized hydrogen. In this context, there should exist a distribution correlation between the dark matter and the HI gas. This is indeed the case, as already remarked by Bosma (1981), Broeils (1992) or Freeman (1993): there is a constant ratio between the surface density of dark matter, as deduced from the rotation curves, and the HI surface density,  $\Sigma_{DM}/\Sigma_{HI} =$

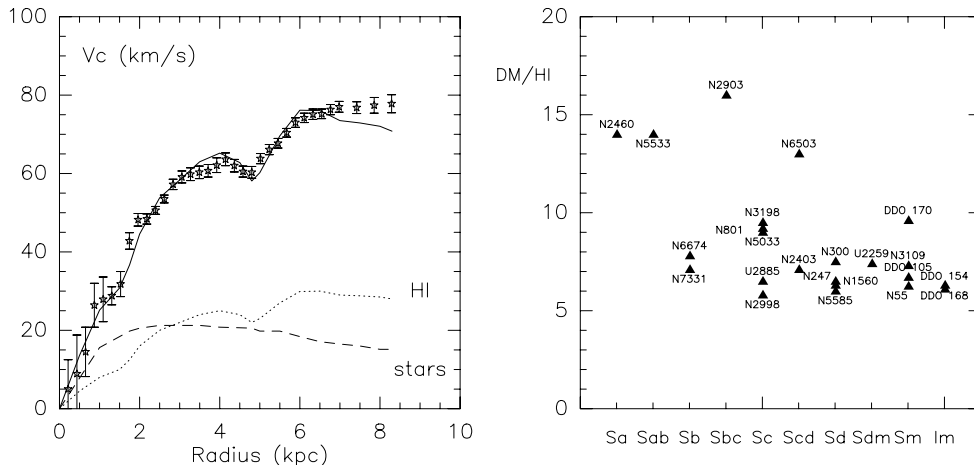


FIGURE 3. *Left*: HI rotation curve of NGC 1560 (dots +error-bars), with the rotation curve due to the HI itself (dotted line) and the stellar component (dash). The full line is the resulting expected rotation curve, when the HI mass has been multiplied by 6.2. *Right*: The ratio of surface densities of dark matter to HI required to explain the rotation curve of galaxies, as a function of type. Data from 23 galaxies have been taken from Broeils (1992) and references therein.

7-10 (cf figure 3, and a recent work by Hoekstra et al. 1999). This ratio is constant with radius in a given galaxy, and varies slightly from galaxy to galaxy, being larger in early-types. However, the dark matter does not dominate the mass in the latter, and therefore the estimate of its contribution is more uncertain. The correlation is the most striking in dwarf galaxies, which are dominated by dark matter. The observed velocity curve is almost exactly proportional to the velocity curve expected from the HI component alone. Figure 3 shows the example of NGC 1560, from Broeils (1992). Let us note that dwarf galaxies represent a hard test for all models of dark matter, since the stellar component does not dominate the mass. They rule out cold dark matter (CDM) profiles (Burkert & Silk 1997), and hot dark matter (HDM) models are also unable to concentrate as much as is observed (Lake 1989, 1990, Moore 1996). Baryonic dark matter is thus required.

#### 4.5. Detection possibilities

If there exists a transition region where the cold  $H_2$  is mixed in part with evolved gas with enough metallicity and dust, it might be possible to detect cold dust emission. Encouraging results have been found by the COBE satellite, concluding to the existence of a cold (4-7K) component with column densities 10 times that of the warm component (at 18K), and more confined to the outer Galaxy (Reach et al. 1998).

Another promising tool for detection is  $H_2$  absorption in the UV electronic lines. The main problem is the low expected surface filling factor of the cold gas ( $\sim 1\%$ ).  $H_2$  has already been detected in front of QSO through intervening galaxies (Foltz et al. 1988, Ge et al 1997); but these observations suffer from severe confusion problem in the Ly $\alpha$  forest. With the Hubble Space telescope, it was not possible to observe the fundamental lines at zero redshift, but it will be possible with FUSE. Let us remark that heavy lines of sight will be impossible to observe, due to obscuration of the background source (e.g. Combes & Pfenniger 1997). Finally, observations of the lowest pure rotational lines of  $H_2$  have suggested some clues for the existence of large quantities of  $H_2$  in galaxies (Valentijn & van der Werf 1999) and should be pursued in external galaxies, at much further radius than was possible with ISO.

## 5. Conclusions

The bulk of the H<sub>2</sub> mass in galaxies is cold and furtive. The main tracer is the CO molecule, but the H<sub>2</sub>/CO conversion ratio is very variable, according to the physical conditions in molecular clouds (density and temperature), but mainly with the metallicity.

Probably because of radial abundance gradients, the molecular gas traced by the CO emission is only observed to extend over the optical disk, while the atomic gas component is prolonged much farther out in radius. Nevertheless, the HI and H<sub>2</sub> at the same radius are tightly correlated, at large-scale (kpc scale). They trace the same spiral structure for example. In the vertical direction, the two components are also well mixed: both reveal a constant vertical velocity dispersion with radius, of comparable amplitude. This suggests that the HI could serve as the tracer of the H<sub>2</sub> component, that would then also extends far out in radius. The constant ratio between dark matter and HI surface densities in galaxies support this hypothesis. If cold molecular gas is a good candidate of baryonic dark matter, observational tests should be pursued: H<sub>2</sub> UV absorption lines may be the best probe, and data from the FUSE satellite will certainly make big advances on the subject.

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